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## Aquatic environment

<table>
<thead>
<tr>
<th>Title</th>
<th>Authors</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three-dimensional hydrodynamic and water quality model for TMDL development of Lake Fuxian, China</td>
<td>Lei Zhao, Xiaoling Zhang, Yong Liu, Bin He, Xiang Zhu, Rui Zou, Youguan Zhu</td>
<td>1355</td>
</tr>
<tr>
<td>Removal of dispersant-stabilized carbon nanotubes by regular coagulants</td>
<td>Ni Liu, Changli Liu, Jing Zhang, Duobai Lin</td>
<td>1364</td>
</tr>
<tr>
<td>Effect of environmental factors on the effectiveness of ammoniated bagasse in wicking oil from contaminated wetlands</td>
<td>Seungjoong Chung, Makram T. Suidan, Albert D. Venosa</td>
<td>1371</td>
</tr>
<tr>
<td>Cationic content effects of biodegradable amphoteric chitosan-based flocculants on the flocculation properties</td>
<td>Zhen Yang, Yabo Shang, Xin Huang, Yichun Chen, Yaobo Lu, Aimin Chen, Yuxiang Jiang, Wei Gu</td>
<td>1378</td>
</tr>
<tr>
<td>Biosorption of copper and zinc by immobilised and free algal biomass, and the effects of metals biosorption on the growth and cellular structure of <em>Chlorella</em> sp. and <em>Chlamydomonas</em> sp. isolated from rivers in Penang, Malaysia</td>
<td>W. O. Wan Maznah, A.T. Al-Fawwaz, Misni Surif</td>
<td>1386</td>
</tr>
</tbody>
</table>

## Atmospheric environment

<table>
<thead>
<tr>
<th>Title</th>
<th>Authors</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Removal characteristics and kinetic analysis of an aerobic vapor-phase bioreactor for hydrophobic alpha-pinene</td>
<td>Yifeng Jiang, Shanshan Li, Zhuowei Cheng, Runye Zhu, Jianmeng Chen</td>
<td>1411</td>
</tr>
<tr>
<td>Characterization of polycyclic aromatic hydrocarbon emissions from diesel engine retrofitted with selective catalytic reduction and continuously regenerating trap</td>
<td>Asad Naemr Shah, Yunshan Ge, Jianwei Tan, Zhizhua Liu, Chao He, Tao Zeng</td>
<td>1449</td>
</tr>
<tr>
<td>Size distributions of aerosol and water-soluble ions in Nanjing during a crop residual burning event</td>
<td>Honglei Wang, Bin Zhu, Lijuan Shen, Hanqing Kang</td>
<td>1457</td>
</tr>
<tr>
<td>Aerosol structure and vertical distribution in a multi-source dust region</td>
<td>Jie Zhang, Qiang Zhang, Congguo Tang, Yongxiang Han</td>
<td>1466</td>
</tr>
</tbody>
</table>

## Terrestrial environment

<table>
<thead>
<tr>
<th>Title</th>
<th>Authors</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect of organic wastes on the plant-microbe remediation for removal of aged PAHs in soils</td>
<td>Jing Zhang, Xiangui Lin, Weimei Liu, Yiming Wang, Jun Zeng, Hong Chen</td>
<td>1476</td>
</tr>
<tr>
<td>Nitrogen deposition alters soil chemical properties and bacterial communities in the Inner Mongolia grassland</td>
<td>Ximei Zhang, Xingguo Han</td>
<td>1483</td>
</tr>
</tbody>
</table>

## Environmental biology

<table>
<thead>
<tr>
<th>Title</th>
<th>Authors</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Augmentation of tribenuron methyl removal from polluted soil with <em>Bacillus</em> sp. strain BS2 and indigenous earthworms</td>
<td>Qiang Tang, Zhiping Zhao, Yajun Liu, Nanxi Wang, Banjun Wang, Yanan Wang, Ningyi Zhou, Shuangjiang Liu</td>
<td>1492</td>
</tr>
<tr>
<td>Microbial community changes in aquifer sediment microcosm for anaerobic anthracene biodegradation under methanogenic condition</td>
<td>Rui Wan, Shuying Zhang, Shuangxun Xie</td>
<td>1498</td>
</tr>
</tbody>
</table>

## Environmental health and toxicology

<table>
<thead>
<tr>
<th>Title</th>
<th>Authors</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular toxicity of earthworms induced by cadmium contaminated soil and biomarkers screening</td>
<td>Xiaohui Mo, Yuhui Qiao, Zhenjun Sun, Xiaohe Sun, Yang Li</td>
<td>1504</td>
</tr>
<tr>
<td>Effect of cadmium on photosynthetic pigments, lipid peroxidation, antioxidants, and artemisinin in hydroponically grown <em>Artemisia annua</em></td>
<td>Xuan Li, Manxi Zhao, Lanping Guo, Luqi Huang</td>
<td>1511</td>
</tr>
</tbody>
</table>

## Environmental catalysis and materials

<table>
<thead>
<tr>
<th>Title</th>
<th>Authors</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influences of pH value in deposition-precipitation synthesis process on Pt-doped TiO&lt;sub&gt;2&lt;/sub&gt; catalysts for photocatalytic oxidation of NO</td>
<td>Shuzhen Song, Zhongyi Sheng, Yue Liu, Haiqiang Wang, Zhongbiao Wu</td>
<td>1519</td>
</tr>
<tr>
<td>Adsorption of mixed cationic-nonionic surfactant and its effect on bentonite structure</td>
<td>Yaxin Zhang, Yan Zhao, Yong Zhu, Huayong Wu, Hongtao Wang, Wening Lu</td>
<td>1533</td>
</tr>
</tbody>
</table>

## Municipal solid waste and green chemistry

<table>
<thead>
<tr>
<th>Title</th>
<th>Authors</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovery of phosphorus as struvite from sewage sludge ash</td>
<td>Huacheng Xu, Pinjing He, Weiwei Gu, Guanzhao Wang, Liming Shao</td>
<td>1525</td>
</tr>
</tbody>
</table>
Enhancing sewage sludge dewaterability by bioleaching approach with comparison to other physical and chemical conditioning methods

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Received 06 October 2011; revised 23 December 2011; accepted 04 January 2011

Abstract
The sewage sludge conditioning process is critical to improve the sludge dewaterability prior to mechanical dewatering. Traditionally, sludge is conditioned by physical or chemical approaches, mostly with the addition of inorganic or organic chemicals. Here we report that bioleaching, an efficient and economical microbial method for the removal of sludge-borne heavy metals, also plays a significant role in enhancing sludge dewaterability. The effects of bioleaching and physical or chemical approaches on sludge dewaterability were compared. The conditioning result of bioleaching by Acidithiobacillus thiooxidans and Acidithiobacillus ferroxidans on sludge dewatering was investigated and compared with the effects of hydrothermal (121°C for 2 hr), microwave (1050 W for 50 sec), ultrasonic (250 W for 2 min), and chemical conditioning (24% ferric chloride and 68% calcium oxide; dry basis). The results show that the specific resistance to filtration (SRF) or capillary suction time (CST) of sludge is decreased by 93.1% or 74.1%, respectively, after fresh sludge is conditioned by bioleaching, which is similar to chemical conditioning treatment with ferric chloride and calcium oxide but much more effective than other conditioning approaches including hydrothermal, microwave, and ultrasonic conditioning. Furthermore, after sludge dewatering, bioleached sludge filtrate contains the lowest concentrations of chroma (18 times), COD (542 mg/L), total N (TN, 300 mg/L), NH4+-N (208 mg/L), and total P (TP, 2 mg/L) while the hydrothermal process resulted in the highest concentration of chroma (660 times), COD (18,155 mg/L), TN (472 mg/L), NH4+-N (381 mg/L), and TP (191 mg/L) among these selected conditioning methods. Moreover, unlike chemical conditioning, sludge bioleaching does not result in a significant reduction of organic matter, TN, and TP in the resulting dewatered sludge cake. Therefore, considering sludge dewaterability and the chemical properties of sludge filtrate and resulting dewatered sludge cakes, bioleaching has potential as an approach for improving sludge dewaterability and reducing the cost of subsequent reutilization or disposal of dewatered sludge.

Key words: sludge; bioleaching; conditioning; filtrate; sludge cake
DOI: 10.1016/S1001-0742(11)60958-3

Introduction
Wastewater treatment plants (WWTPs) are increasing rapidly in China because of more stringent government regulations for water quality. By 2011, the number of WWTPs has reached about 3080 with the amount of treated wastewater being 1.25x10^8 m^3/day. Sludge production is estimated to more than 6,000,000 dry ton per year. It is well known that the waste activated sludge generated from the secondary settling tank of the activated sludge process in municipal treatment facilities is very difficult to dewater (Zhao and Bache, 2002; Neyens and Baeyens, 2003). Currently, dewatered sludge obtained through the addition of cationic-synthetic polymers such as cationic polyacrylamide (PAM) followed by conventional mechanical dewatering often contains moisture as high as 80%, which results in large amounts of sludge to be transported and disposed. With more stringent sludge disposal regulations, low water content in the sludge cake is required to improve subsequent reutilization or disposal of sludge cake. For example, sludge cake of higher dry solid content will increase the energy efficiency of incineration, decrease the requirement for supplemental bulking agents during composting, and reduce the amount of leachate in landfills (Lo et al., 2001). Thus, producing dewatered sludge of high DS% (percentage dry solids content) of 40% or above through sludge conditioning and then mechanical dewatering is of paramount importance for both the reduction of the amount of sludge produced and the cost of subsequent disposal. Efficient sludge conditioning can alter the sludge structure and physical states of water in sludge, change the bound water in sludge into free water, and eventually improve sludge dewatering characteristics to achieve a high solid content (Neyens et al., 2003; Pan et al., 2003). For a few decades, many efforts have been devoted to improving sludge dewaterability through sludge conditioning prior to mechanical dewatering, predominantly with a focus on physical or chemical approaches such as hydrothermal (Neyens and Baeyens, 2003; Hang et al., 1983), microwave...
(Wojciechowska, 2005; Yu et al., 2009), ultrasonic (Xu and Wang, 2009; Shao et al., 2010; He et al., 2011), and chemical conditioning (Chen and Wu, 2009; Turchiuli and Fargues, 2004; Deneux-Mustin et al., 2001).

It has been known for many years that thermal conditioning gives an improvement in the dewaterability of sludge, because hydrothermal conditioning of sludge at 170°C for 90 min results in a decrease in bound water content (Neyens and Baeyens, 2003; Xun et al., 2009). It has been noted that microwave radiation readily leads to the disruption of sludge microorganism cells and then the release of the bound water in sludge. Consequently, the specific resistance to filtration (SRF) of conditioned sewage sludge is decreased by 27% through 180 sec of microwave treatment (Wojciechowska, 2005). Tian et al. (2006) also have reported some similar results when sludge is conditioned with microwave radiation at 900 W for 50 sec. Ultrasonic treatment is reported to be capable of both positive and negative effects on sludge dewatering (Bougrier et al., 2006; Na et al., 2007; Wang et al., 2006). For example, Na et al. (2007) have observed that ultrasonic treatment of waste activated sludge improves the dewaterability as evidenced by the decrease in capillary suction time (CST) with increasing ultrasonic energy. The CST decreased to <10 sec for sludge treated with >2000 kJ/L of ultrasonic energy for 53 sec for untreated sludge.

In contrast, Wang et al. (2006) demonstrated that ultrasonic disintegration deteriorated sludge dewaterability, as shown by an increase in SRF or CST. Regarding the chemical conditioning, ferric chloride and calcium oxide are typically added to sludge in order to improve sludge dewaterability (Chen and Wu, 2009; Krishnamurthy and Viraraghavan, 2005; Chen et al., 2000; Li et al., 2006). It is found that sludge can be concentrated quickly and further dewatered by chamber filter pressing into sludge cake with moisture below 60% if sludge is conditioned by the addition of 24% (dry basis) of ferric chloride and 68% (dry basis) of calcium oxide (Chen and Wu, 2009).

Based upon the literature mentioned above, it has been found that conventional physical conditioning such as thermal, microwave and ultrasonic treatment require energy input into sludge systems to destroy the cells or change the sludge/water distribution. When sludge is conditioned with ferric chloride and calcium oxide, large amounts of inorganic substances are used and incorporated into the sludge. Consequently, the organic matter or thermal value of the dry sludge cake is drastically decreased, which is unfavorable for subsequent disposal or reutilization of the sludge cake if sludge is incinerated or used for land application. Thus, there is an urgent need to seek a suitable and cost-effective technology to improve sludge dewaterability without altering the organic matter content or thermal value.

In the last two decades, bioleaching technology has been developed as a potential microbial method to remove heavy metals from sewage sludge, facilitated by A. thiooxidans and A. ferrooxidans (Wong et al., 2004; Tyagi et al., 1988; Zheng et al., 2009). Surprisingly, sludge dewaterability appears to be improved after bioleaching (Song and Zhou, 2008; Liu and Zhou, 2009), as shown by the fact that SRF of bioleached sludge is drastically reduced in comparison to fresh sludge. However, during the past years, the study of sludge bioleaching has focused on the removal of sludge-borne heavy metals instead of the issue of sludge dewaterability.

Comparing the effects of physical and chemical methods with bioleaching technology on sludge conditioning, in order to evaluate the advantages and problems of these conditioning methods, will improve our understanding in developing bioleaching as a potential technology. However, little information about this issue is available. Up to now, the variation of nutrients in the filtrate and dewatered sludge cake from different conditioning methods have not been compared systematically in previous studies.

Therefore, the objectives of the present study are to investigate the effect of bioleaching on sludge dewaterability and the chemical properties of the resulting filtrate and sludge cake, in comparison with other physical or chemical conditioning approaches.

1 Materials and methods

1.1 Municipal sewage sludge sampling

Sewage sludge used in this work was collected from the sludge-thickening pond of the High-Tech Park Wastewater Treatment Plant located in Suzhou City, Jiangsu Province, China. pH, SRF, and CST of the selected sludge were determined immediately after collection while total solid content was measured by oven-drying at 105°C. The content of TN, TP, and organic matter in the sludge (dry basis) was determined according to the methods of Bremner (1996), Kuo (1996), and Nelson and Sommers (1996).

The selected properties of the selected sludge as the following: pH 7.48 ± 0.02; SRF 4.65 × 10^13 ± 0.10 × 10^13 m/kg; CST 62.6±3.1 sec; total solid 2.95% ± 0.04%; organic matter 51.2% ± 0.3% dry basis; TP 2.09% ± 0.10% dry basis and TN 2.45% ± 0.14% dry basis.

1.2 Sludge conditioning trials

The experiment was designed with three replications and included the following treatments:

1. (1) Fresh sludge (FS): fresh sludge without any conditioning process.

2. Hydrothermal conditioning: 300 mL samples of fresh sludge placed in 500 mL Erlenmeyer flasks were treated in an Automatic High Pressure Steam Autoclave (D-1, Beijing Jinhaixin Pressure Vessel Manufacture Co., Ltd., China) at 121°C, 0.12 MPa for 2 hr to obtain hydrothermally-conditioned sludge (HS). As is well known, microbial cells should be disrupted at 121°C. Therefore, we chose 121°C in this treatment, in consideration of energy consumption.

3. Microwave conditioning: 300 mL samples of fresh sludge placed in 500 mL Erlenmeyer flasks were taken into a microwave generator (LG-wp700, LG Electronics Appliance Co., Ltd., Tianjin, China) with a reaction time of 50 sec (Tian et al., 2006) at 2450 MHz and 1050 W.
generate microwave-conditioned sludge (MS).

(4) Ultrasonic conditioning: 300 mL samples of fresh sludge placed in 500 mL Erlenmeyer flasks were treated in an ultrasonic generator (kq-250B, Kunshan Ultrasonic Instruments Co., Ltd., Jiangsu, China) with ultrasonication for 2 min according to Xu and Wang (2009) to produce ultrasonically-conditioned sludge (US). The ultrasonic power and specific energy dosage were 250 W and 3390 kJ/kg total solids (TS), respectively.

(5) Bioleaching conditioning: The effect of bioleaching on sludge dewaterability was investigated through flask experiments with co-inoculation of Acidithiobacillus ferrooxidans TS6 and Acidithiobacillus thiooxidans LX5. Thirty milliliters of bioleached sludge as inoculum was added to 500 mL of sludge in 500 mL Erlenmeyer flasks and stirred at 500 r/min for 15 sec, then 6 g of calcium oxide powder (<0.15 mm) (Sinopharm Chemical Reagent Co., Ltd., Shanghai, China) was added into the above flasks and stirred again at a low velocity (50 r/min) for 15 min according to Chen and Wu (2009) to obtain chemically-conditioned sludge (CS).

After the above treatments, all conditioned sludge samples were withdrawn and analyzed for pH, color, SRF, CST, and sedimentation rate. Then, the dewatering of these sludge samples was conducted in duplicate through a vacuum filter experiment. Briefly, 50 mL sludge samples with or without conditioning were poured into a Buchner funnel to filter under 640 mmHg pressure. The filtrate and sludge cake were collected and determined for COD, TN, TP, NH$_4^+$-N, chroma, and organic matter.

### 1.3 Analytical methods

pH was monitored using a pHS-3C model digital pH-meter (pHS-3C, Shanghai Precision & Scientific Instrument Co., Ltd., China) with the Pt-Ag/AgCl electrode system. The color of sludge was measured using the Munsell color book (Munsell color Company, 1994). SRF and CST were determined by the Buchner funnel method (Lu et al., 2003) and a CST apparatus (340M, Triton Electronics Ltd., England), respectively. The sedimentation rate of conditioned sludge was determined according to the method described by Zhou et al. (2004). Briefly, the conditioned sludge samples were poured into 100 mL cylinders and then sludge volume was visually measured periodically.

Chroma of the filtrate was determined with the multiple dilution method (Hu et al., 2005; Wang et al., 2008). The COD was determined by the potassium dichromate method. TN, TP, and NH$_4^+$-N of the filtrate were measured according to APHA (1995). The dewatered sludge cake was harvested after 25 min for dewatering through vacuum filtration, dried to constant weight at 105°C, and measured for organic matter, TN, and TP. The organic matter content of the sludge cake was measured according to the method described by Nelson and Sommers (1996). TN was determined following the Kjeldahl method (Bremner, 1996), while TP was measured by the vanadium molybdate yellow colorimetric method (Kuo, 1996).

### 1.4 Statistical analyses

Data were analyzed using SPSS (SPSS 20.0 for windows). Means and standard deviation of triplicates were determined and all the figures presented include standard errors of the data. Significant differences among treatment means were determined using the Student-Newman-Keuls test ($P < 0.05$).

### 2 Results and discussion

#### 2.1 Variations of pH, color, and odor after sludge conditioning

The variations of pH, color, and odor of sludge with and without the conditioning through different methods are given in Table 1.

Sludge pH increased from 7.48 to 8.56 after sludge hydrothermal conditioning, which probably was due partly to the destruction of microbial cells in sewage sludge after hydrothermal conditioning (Kepp et al., 2000; Barjenbruch et al., 1999), and partly to the hydrolysis of the protein to ammonia during this process. The sludge exhibited a strong sourness after hydrothermal conditioning. On the contrary, sludge pH gradually decreased from initial pH 7.48 to final pH 2.79 after bioleaching. Most studies also reported that the pH value tended to decrease during bioleaching (Zhang et al., 2009; Sreekrishnan et al., 1993; Chartier and Couillard, 1997). In addition, the odor of the sludge quickly disappeared during the bioleaching process, and the sludge took on an earthy aroma and yellow-brown appearance from the initial black or grey-black. In the case of the chemical conditioning process, pH value sharply increased from initial 7.48 to 12.20. The color of the sludge changed from black to dark gray after chemical conditioning.

#### Table 1 Variations of pH, color, and odor after sludge conditioning with different methods

<table>
<thead>
<tr>
<th>Conditioning method</th>
<th>pH</th>
<th>Color</th>
<th>Odor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh sludge</td>
<td>7.48 ± 0.02</td>
<td>SY 2/1</td>
<td>Strong odor</td>
</tr>
<tr>
<td>Hydrothermal</td>
<td>8.56 ± 0.02</td>
<td>SY 2/1</td>
<td>The odor diminished, but sludge displayed strong sourness after conditioning</td>
</tr>
<tr>
<td>Microwave</td>
<td>7.48 ± 0.02</td>
<td>SY 2/1</td>
<td>Strong odor</td>
</tr>
<tr>
<td>Ultrasonic</td>
<td>7.48 ± 0.02</td>
<td>SY 2/1</td>
<td>Strong odor</td>
</tr>
<tr>
<td>Bioleaching</td>
<td>2.79 ± 0.08</td>
<td>2.5Y 7/3</td>
<td>The odor disappeared, and sludge exhibited earthy aroma after bioleaching</td>
</tr>
<tr>
<td>Chemical</td>
<td>12.20 ± 0.05</td>
<td>SY 4/1</td>
<td>Offensive odor</td>
</tr>
</tbody>
</table>
conditioning. In addition, an offensive odor was released during sludge conditioning using calcium oxide. However, no significant changes of pH, color, or odor of sludge were observed after ultrasonic or microwave conditioning in this work.

2.2 Assessment of sludge dewaterability with or without sludge conditioning

SRF, CST, and sedimentation rate have been widely used to assess sludge dewaterability (Feng et al., 2009; Lee and Liu, 2001; Liu and Zhou, 2009; Chen et al., 2004). The variations of SRF and CST are presented in Fig. 1. Generally, a higher SRF value or longer CST indicates worse sludge dewaterability (Feng et al., 2009; Lee and Liu, 2001).

As shown in Fig. 1, the SRF and CST of fresh sludge were 4.65 × 10^{13} m/kg and 62.6 sec, respectively. However, sludge SRF increased to 26.07 × 10^{13} m/kg and the corresponding CST was 1390.1 sec when sludge was conditioned with the hydrothermal method (Fig. 1). These results indicated that hydrothermal conditioning led to the deterioration of sludge dewaterability. The finding was in agreement with the results obtained by Neyens et al. (2003), who also observed that the sludge CST value increased from 44.3 to 198 sec when sludge was conditioned at 155°C for 1 hr. This was probably because the proportion of small molecules increased during the sludge hydrolysis processes, and these small molecule substances could easily block the filter during sludge filtration. However, Xu et al. (2009) found that the bound water content in dewatered sludge with 82.0% of moisture was decreased from 3.6 g/g dry solid to lower than 1.0 g/g. The lowest bound water content was 0.592 g/g at 170°C for 90 min. Perhaps the temperature plays a pivotal role in sludge hydrothermal conditioning. The sludge dewaterability may be enhanced only when the temperature is increased to 170°C or above. Undoubtedly, the sludge hydrothermal conditioning is a higher energy consumption process, resulting in a higher operation cost.

Sludge dewaterability also was not improved by sludge microwave conditioning, as SRF and CST were slightly decreased from 4.65×10^{13} m/kg and 62.6 sec to 3.29×10^{13} m/kg and 57.7 sec. After ultrasonic conditioning, SRF and CST increased to 5.49×10^{13} m/kg and 172.5 sec. These results were in agreement with Xu and Wang (2009) and Chu et al. (2001), who found that the CST increased markedly if sludge was treated by ultrasonic conditioning. Tian et al. (2006) and Wang (2006) also reported that sludge dewaterability deteriorated because the sludge structure changed, and the sludge viscosity increased unexpectedly when sludge was conditioned by microwave or ultrasonic treatments.

However, it is worthy to note that bioleaching conditioning or chemical conditioning using ferric chloride and calcium oxide could strongly enhance the dewaterability of sewage sludge, as indicated by the reduction of 93.1% for SRF and 74.1% for CST after sludge bioleaching. Likewise, chemical conditioning also led to the reductions of 93.8% and 71.4% for sludge SRF and CST.

The changes in sludge sedimentation rate after sludge conditioning with different methods are provided in Fig. 2.

The sedimentation rate of fresh sludge was 14% in 20 hr, but only 1% for hydrothermally-conditioned sludge within the same time. After microwave conditioning, the sedimentation percentage of sludge increased with an increase in settlement time and eventually attained a plateau value of 12% at 8 hr. On the contrary, the sedimentation efficiency reached 19% at 20 hr for sludge conditioned by ultrasonic conditioning. Compared to the control (fresh sludge), the settling properties of bioleached sludge and chemically conditioned sludge increased by 1.21 and 0.93 fold, respec-

![Fig. 1 SRF and CST of differently conditioned sludge. FS: fresh sludge; HS: hydrothermally-conditioned sludge; MS: microwave-conditioned sludge; US: ultrasonically-conditioned sludge; BS: biolached sludge; CS: chemically-conditioned sludge. Columns labeled in the histograms with the same letter are not significantly different at P < 0.05. The vertical T-bars indicated standard error about the means.](image)

![Fig. 2 Sedimentation rate of differently conditioned sludge in 20 hr.](image)
tively. Again, this indicated that bioleaching and chemical conditioning with ferric chloride and calcium oxide played a notable role in improving sludge dewatering.

Ultrasonic conditioning could, to some extent, improve the settling properties of sludge. The phenomenon might be attributable to the fact that sludge flocs were disrupted under ultrasonic conditioning (Zhang et al., 2007). However, excessive energy input into the sludge system tended to significantly deteriorate sludge dewaterability due to the disruption of floc structure and release of intracellular and extracellular materials. For example, Emir and Erdincler (2006) found that sludge dewaterability could be seriously deteriorated when the energy dosage was beyond 4400 kJ/kg TS. In the present study, sludge dewaterability was markedly deteriorated only when the energy dosage reached 3390 kJ/kg TS. Undoubtedly, the optimal energy dosage for sludge dewatering might be different for sludge with different physicochemical properties, which could be used to explain why both positive and negative effects of ultrasonic conditioning on sludge dewaterability were found in previous studies (Bougrier et al., 2006; Na et al., 2007; Wang et al., 2006).

Correspondingly, it was found that the moisture content of dewatered sludge cake obtained through vacuum filtration was 95.7% for fresh sludge, 96.5% for hydrothermally conditioned sludge, 95.7% for ultrasonically conditioned sludge, 95.2% for microwave conditioned sludge, 80% for bioleached sludge, and 74.4% for chemically conditioned sludge. Clearly, bioleaching or chemical conditioning was effective in improving sludge dewaterability. In a practical engineering application of bioleaching located in the Wuxi Taihu Wastewater Treatment Plant, Wuxi City, China, it was reported that the moisture of bioleached sludge cake obtained through chamber filter press dewatering devices was always lower than 60% (data not shown). Other workers also observed that sewage sludge could be filter press dewatered to a 40% DS sludge cake after sludge chemical conditioning (Chen and Wu, 2009).

2.3 Water quality of filtrate from dewatering-conditioned sludge

Chroma of the filtrate obtained from the dewatering of hydrothermally-treated sludge through a vacuum filter was increased to 660 times from the initial 100 times of the filtrate from fresh sludge without any conditioning. The filtrate chroma of sludge from microwave or ultrasonic conditioning treatment was 175 or 180 times, respectively. Surprisingly, the filtrate chroma of bioleached sludge drastically decreased to 18 times from the initial 100 times for fresh sludge with 82% removal efficiency of chroma. It was almost colorless by visual observation (Fig. 3). A similar trend was also found for chemically conditioning sludge with ferric chloride and calcium oxide. The chroma decreased to 50 times with 50% chroma removal efficiency. Clearly, sludge conditioning using bioleaching resulted in the highest removal efficiency of filtrate chroma among these different conditioning methods as shown in Fig. 3.

The variations of COD, TN, TP, and NH$_4^+$-N in the filtrates obtained from dewatering conditioned sludge are illustrated in Fig. 4. After hydrothermal conditioning of sludge followed by vacuum filtration, the filtrate contained a high concentration of COD (18,155 mg/L), TN (472 mg/L), TP (191 mg/L), and NH$_4^+$-N (381 mg/L), which were 17.6, 2.34, 1.61, and 2.54 times higher than those from sludge without any conditioning (COD: 1031 mg/L; TN: 202 mg/L; TP: 119 mg/L and NH$_4^+$-N: 150 mg/L), respectively. These results were consistent with the report of Xun et al. (2008), who also found that sludge hydrothermal conditioning significantly increased the levels of COD, TN, TP, and NH$_4^+$-N in the filtrate due to the hydrolysis of carbohydrates, protein, fats, and nucleic acids in sludge solids. Bougrier et al. (2006) noted that the thermal treatment of waste activated sludge led to a higher concentration of COD in the filtrate compared to sonication or ozonation pre-treatment.

In the present study, after microwave or ultrasonic conditioning, COD, TN, and NH$_4^+$-N in the filtrate were slightly increased, by only 21.1% ± 4.60% for COD, 45.5% ± 12.4% for TN, and 21.0 ± 17.0% for NH$_4^+$-N, while TP did not significantly change, by only (4.20 ± 2.50%). The short time for sludge conditioning by microwave or ultrasonic treatments perhaps was responsible for the small increase of COD, TN, and NH$_4^+$-N of the filtrate. In contrast, the concentrations of COD and TP in the filtrate from bioleached sludge were drastically decreased to 542 mg/L for COD and 2 mg/L for TP with 47% and 98% removal efficiencies for COD and TP, respectively, in comparison with the filtrate from untreated fresh sludge. The almost complete removal of TP in the filtrate of bioleached sludge might be attributed predominately to the formation of FePO$_4$ precipitate due to the binding of soluble P with Fe$^{3+}$ resulting from Fe$^{2+}$ bio-oxidization by A. ferrooxidans LX5, and partly to uptake by bioleaching microorganisms. This conjecture also could be supported by the results of the sludge chemical conditioning treatment with ferric chloride and calcium oxide, in which TP in the filtrate was significantly decreased to 8 mg/L from 119 mg/L in the filtrate of fresh sludge. However, TN and NH$_4^+$-N in the filtrate of the bioleached sludge slightly increased to 300 and 208 mg/L in comparison to those in the control (the filtrate of fresh sludge). When sludge was...
chemically pre-treated using ferric chloride and calcium oxide, COD, TN, and NH$_4^+$-N in the filtrate of the pre-treated sludge significantly increased to 1250, 549, and 353 mg/L, respectively, which were 1.21, 2.72, and 2.35 times as high as those for COD, TN, and NH$_4^+$-N in the control. The hydrolysis or solubilization of sludge organic matter, including protein and carbohydrate, facilitated by lime perhaps was a main reason for the higher concentration of COD, TN, and NH$_4^+$-N in the filtrate because of the presence of a higher pH of 12.20 due to the conditioning with ferric chloride and calcium oxide (Feng and Huang, 2011; Li et al., 2005; Samaras et al., 2008).

2.4 Content of organic matter, TN, and TP in dewatered sludge with or without pre-treatment

As shown in Fig. 5, the dewatered sludge cakes from bioleaching, hydrothermal, microwave, and ultrasonic pre-treatments through vacuum filter dewatering exhibited similar contents of TN (2.03%–2.21%), TP (1.96%–2.17%), and organic matter (48%–49.7%), which were very close to those from fresh sludge without any pre-treatment, with 51.2% of organic matter, 2.45% of TN, and 2.09% of TP. This indicated that the bioleaching pre-treatment hardly affected the content of organic matter, TN, and TP of the sludge dry solid. However, organic matter, TN, and TP in the dewatered sludge cake from the chemical conditioning treatment were decreased dramatically by 58%, 42.5% and 52.7%, respectively, because of the introduction of large amounts of inorganic substances into the sludge matrix. As expected, the sludge cake obtained through chemical conditioning with large amounts of calcium oxide was unfavorable for land application or incineration.

3 Conclusions

The dewaterability of municipal sewage sludge could be markedly enhanced after bioleaching or chemical conditioning with ferric chloride and calcium oxide in comparison with other conditioning approaches, including hydrothermal, ultrasound, and microwave treatments. Furthermore, bioleached sludge filtrate obtained through vacuum filtration contained much lower concentrations of chroma, COD, TN, TP, and NH$_4^+$-N than those of other conditioning treated sludge, especially for TP. Only 2 mg/L of TP existed in the filtrate from bioleached sludge, indicating that 98% of the TP in fresh sludge filtrate could be removed if the sludge was pre-treated by bioleaching. Unlike chemical conditioning by addition of ferric chloride and calcium oxide, sludge bioleaching did not result in the obvious reduction of organic matter, TN, and TP in the resulting dewatered sludge cakes, which was similar to other conditioning approaches including hydrothermal, ultrasound, and microwave methods. Taking sludge dewaterability and the chemical properties of the sludge filtrate and dewatered sludge cake into account, bioleaching has potential as an approach in improving sludge dewatering and subsequent disposal or reutilization of pre-treated sludge cake.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 21177060, 20977048) and the National High Technology Research and Development...
<table>
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<tr>
<th>Treatment</th>
<th>Total N (g/kg)</th>
<th>Total P (g/kg)</th>
<th>Organic matter (%)</th>
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<tr>
<td>FS</td>
<td>12</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>HS</td>
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</tr>
<tr>
<td>US</td>
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<td>16</td>
<td>16</td>
</tr>
<tr>
<td>BS</td>
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</tbody>
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**Fig. 5** Total N, total P, and organic matter of dewatered sludge cake after sludge dewatering with and without conditioning. Columns labeled in the histograms with the same letter are not significantly different at \( P < 0.05 \). The vertical T-bars indicated standard error about the means.

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